WHOI DOCUMENT COLLECTION

TN-1365
AD-A004 931

Technical Note N-1365

GUIDELINE SYSTEMS FOR DEEP-SEA DEPLOYMENTS

by

Francis C. Liu

December 1974

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

Approved for public release; distribution unlimited.

CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

TA
417
.N3
no. N1365

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TN-1365	2. GOVT ACCESSION NO. DN244128	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* GUIDELINE SYSTEMS FOR DEEP-SEA DEPLOYMENTS		5. TYPE OF REPORT & PERIOD COVERED Final; Jul 1972–Oct 1973 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Francis C. Liu		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62755N YF53.535.004.01.004
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12. REPORT DATE December 1974 13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Guideline system, guide frame, anchor mating, load handling, line entanglement, deep sea construction, experiment.

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A guideline is a mechanical cable stretched between the surface and the seafloor to direct a suspended payload to a seafloor site. Two series of sea tests were conducted: one at the 600-foot depth and the other at the 4,500-foot depth. The results of these two sea tests have shown that, after the lift line and the guideline are sufficiently uncoupled from surface excitation, single and double guideline

continued

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

MBL/WHOI

0 0301 0040212 9

20. Continued

systems can be operated in water depths to at least 4,500 feet without serious entanglement problems. Payload rotation produced during the deployment test was found to be small and results from variations in static forces. The design of guideline hardware and at-sea handling is discussed. In addition to surface motion compensation, a means for releasing in-line torque must be provided to achieve entanglement-free operations.

Library Card

Civil Engineering Laboratory
GUIDELINE SYSTEMS FOR DEEP-SEA DEPLOYMENTS, by
Francis C. Liu
TN-1365 35 p. illus December 1974 Unclassified

1. Guideline system 2. Load handling I. YF53.535.004.01.004

A guideline is a mechanical cable stretched between the surface and the seafloor to direct a suspended payload to a seafloor site. Two series of sea tests were conducted: one at the 600-foot depth and the other at the 4,500-foot depth. The results of these two sea tests have shown that, after the lift line and the guideline are sufficiently uncoupled from surface excitation, single and double guideline systems can be operated in water depths to at least 4,500 feet without serious entanglement problems. Payload rotation produced during the deployment test was found to be small and results from variations in static forces. The design of guideline hardware and at-sea handling is discussed. In addition to surface motion compensation, a means for releasing in-line torque must be provided to achieve entanglement-free operations.

CONTENTS

INTRODUCTION

Future underwater construction and salvage operations for the Navy may require extensive load-handling capabilities for emplacement, suspension, recovery, and assembly of large, heavy structures at predetermined seafloor locations at depths to 20,000 feet. Guideline systems are a potential solution for these problems. The required capabilities include not only high-tension lifting but also seafloor positioning and mating. In general, new load-handling systems must minimize the dynamic loading in the lift line and the large amplitude oscillatory motion of the payload near the seafloor. Additional hardware is needed to provide the required capabilities for accurate seafloor positioning, precise alignment, and repeated returns to the same seafloor site.

Description of the System

A guideline system employs mechanical cables to restrict the lateral drifting of a payload suspended from a flexible lift line and is composed of four basic components (Figure 1): surface support, guideline, anchor, and guide frame. The guideline is either a steel or a synthetic rope which stretches nearly vertical between the surface support and the anchor. The guide frame is a rigid truss for maintaining a fixed distance between the payload and the guideline. As the payload is raised or lowered by a lift line, the guide frame slides freely along the guideline. The lateral motion of payload is, thus, controlled by the guideline system. The number of guidelines in a system can vary from one to several depending on the degree of restriction of motion desired. Figure 2 presents a dry-land simulation of a test of a double guideline system.

Objectives of the Sea Tests

The purpose of this investigation was to obtain a better understanding of the behavior of guideline systems by conducting controlled sea tests. It was intended to identify the difficulties and problems involved in hardware design, motion analysis, and at-sea operation. Once sufficient field data were obtained, then procedures for the design, deployment, and operation of guideline systems could be established for future projects.

The main emphasis of this study was on reducing the probability of guideline entanglement. Field tests were designed to show that with proper precautions, guideline systems could be operated without line entanglement. As a secondary interest, the mechanism of mating two structural modules on the seafloor by using a guideline system was studied. It was intended to demonstrate that the capacity of a gravity anchor could be increased

by adding modular weights to the anchor after its implant and that the alignment of the modules could be controlled by properly designed guideline and bottom guide posts.

Scope of the Study

The scope of this work covers two ocean experiments: the first was a series of parametric tests of a system to a depth of 600 feet, and the second was a series of validation tests to a depth of 4,500 feet. Attempts at mating two structures of basic shapes were included at both depths. The quantitative analysis of the guideline performance data as well as a qualitative evaluation of the design, deployment, and operation of the guideline components are documented. A discussion of the experimental results is given in this document along with recommendations on the design and operation of guideline systems.

BACKGROUND

A flexible guideline system is simple and inexpensive; yet effective as a means of restricting the lateral motions of a payload throughout its vertical travel in the water column. The components of the system are readily available as off-the-shelf items. However, the most serious drawback to the system is believed to be its apparent low reliability, caused mainly by line entanglement.

Guidelines have been used in shallow-water undersea oil-well drilling by offshore oil industries as the most efficient, proven technique for vertical guidance [1]. The main application of the guideline system is for subsea well-head completions. Large well-head equipment, such as blow-out preventers, have been lowered and assembled under the sea, using guidelines for restricting lateral and rotational motion and guide posts for seafloor alignment. In addition, more advanced, manned, completion concepts, such as Lockheed's new well-head completion chamber [2] and Deep Oil Technology's maintenance submersible [3], utilize the concept of multiple guidelines. Although such hardware systems are being developed and tested in shallow-water depths, documentation of guideline design and operation is not available in the open literature.

The Navy needs to use guideline systems in much deeper water than does industry. As a start in developing this capability, guideline systems have been adopted in two major Navy experiments, both of which have been conducted at relatively shallow depths (600 feet). During the SEALAB III [4] and SEACON I [5] emplacements, guideline systems using two guidelines were employed. These systems were designed with little engineering data and minimum analysis. However, the generally satisfactory performance of these systems encouraged further improvement in hardware design and stimulated more rigorous examination of the entanglement problem encountered at deep depths.

A preliminary guideline test was conducted in 1969 in 800 feet of water with a single guideline [6]. Line tensions in both guideline and lift line were measured, but payload motion was not measured; and current measurements were incomplete. Nevertheless, it was encouraging to find that no entanglement was observed during this test.

The guideline system may be the answer to many seafloor construction problems. The system can be used to guide the vertical lifting and lowering of heavy, bulky materials or structural components; the structure, for example, could be an underwater cable car for surface-to-seafloor transportation. Most important, however, is the potential application of the guideline system for remote assembly of prefabricated structural modules on the seafloor. Such construction techniques would not only allow the construction of integrated, large structures with limited equipment but also would allow covertness during implant.

The immediate application of the guideline system is deep-water salvage and rescue operations and the addition of weights to gravity anchors.

SEA TESTS

The sea tests were performed in two stages. The first series of tests, conducted in 600 feet of water, was designed to obtain information on the effects of various parameters on the static and dynamic response of the guideline system. The second series of tests was conducted in 4,500 feet of water to verify the results from the shallow-water tests for entanglement-free operation of guideline systems. Table 1 presents a summary of all sea tests.

Hardware

Guidelines. The guidelines used in the shallow-water tests were 3/4-inch-diameter; 2-in-1 braided nylon ropes; and 1/2-inch-diameter, 6 x 19 wire ropes. In the deep-water tests, only 3/8-inch-diameter, torque-balanced steel wire rope with a polyethylene jacket was used. The lower ends of the guidelines were connected to the guide posts by roller-bearing swivels (Figure 3) to avoid torque accumulation in the guidelines.

Guide Posts and Anchor Blocks. Each guide post was a 3-1/2-inch-diameter pipe section with one end embedded in a concrete anchor block. The top end of the post was tapered and was topped by a lift ring. A notched guide cylinder fabricated of 4-inch pipe was welded on the 3-1/2-inch-diameter pipe for the bottom mating of the anchor block and the add-on block. The single anchor block measured 4 x 4 x 2 feet; the double anchor block measured 4 x 10 x 2 feet. A male conical catch was embedded in the middle of the double block, and the guide posts were embedded 3 feet on either side of the catch (Figure 4). The catch, when

Table 1. Summary of Sea Tests

Test No.	Water Depth (ft)	Number of Guidelines	Guideline Material	Submerged Weight of Load (lb)	Guide Frame Span
1	600	2	steel	2,760	3
2	600	2	steel	5,560	3
3	600	2	nylon	5,560	3
5	600	1	steel	5,560	9
6	600	1	steel	2,760	9
7	600	1	steel	2,760	6
8	600	1	steel	5,560	6
9	600	1	steel	5,560	3
10	600	1	steel	2,760	3
12[a]	600	1	steel	2,760	3
M1[b]	600	1	steel	1,380	0
D1	4,500	2	steel	5,560	3
D2	4,500	2	steel	2,760	3
D3	4,500	1	steel	5,560	3
MD1[b]	4,500	1	steel	1,380	0

[a]Horizontal anchor drift was 50 feet.

[b]Anchor-mating experiment.

the release mechanism was connected to it, served as a lift point for the lowering of the double block. The modular add-on block measured 4 x 4 x 1 feet, and had a 5-inch hole in the middle of it. The lower portion of this hole has the same shape and dimensions as the guide cone skirt. On the top of the hole, a catch was attached for emplacement and retrieval. A guide cylinder made of 4-inch pipe was welded to the inner wall of the 5-inch tubular hole. A notched lower edge of this guide cylinder fits with the top edge of the guide cylinder on the guide post. During the mating of the add-on block to the guideline anchor, the guide plates force the add-on block to re-orient and match each other (Figure 5).

Guide Frame. A versatile guide frame, a rectangular truss fabricated of steel pipes and angles, was designed for use in both single and double guideline systems. Two or more such trusses can be quickly bolted together to make a longer guide frame. For a single guideline system, a guide cone and a lift member are attached on either side of the guide frame.* For a double guideline system, a guide cone is installed on either side of the guide frame, and the lift member is inserted at the middle, between the trusses (Figure 2).

Guide Cones. The guide cones were made of short sections of standard 5-inch steel pipe and steel plates. The plates formed a conical skirt below the pipe section to guide the guide post into the guide cone. A vertical slot cut along the side of the guide cone allowed the quick insertion and release of the guideline. Another function of the skirt was to prevent severe bending of the guideline against the sharp edge of the steel pipe section. Figure 6 shows a guide cone used in the first series of sea tests. The fin-like plate below the guide cone in Figure 6 was one of the supports for the current meter.

A latch was designed to block the opening and to keep the guideline inside the guide cone. The wing nuts could be loosened and the latches opened to allow passing of a guideline. For later tests, a metal strip was attached to the latches to completely cover the slot, and the open end of the tube was reinforced by a peripheral stiffener.

Mechanical Release. A mechanical release (Figure 7) was developed for placing or retrieving objects from the seafloor. The release basically consists of three barrel hooks hinged to three flanges. The flanges, spaced 120 degrees apart, are welded on the outside of a section of steel pipe. Each hook is controlled by a spring with one end fastened to the flange. There are two places that the free end of the spring can be attached. When the spring is attached to the top of the hook, the tip of the hook tends to close into the retrieval position (Figure 7). When the spring is attached to the hook below the hinge point, the hook is forced to open into the release position (Figure 8).

---

*Two guide cones, one above the other, were used in earlier tests; a single guide cone worked better for deck handling.

The release works only with mushroom-shaped male conical catches preinstalled on a payload. The conical skirt forces the hooks to stay closed in release mode as long as tension is maintained in the lift line. Both the release and the catch can slide along a guideline.

Payload. The payloads for the sea tests were a sphere and a block, both fabricated of concrete. Test load L1, the sphere, was 5 feet in diameter and weighed 9,260 pounds in the air and 5,560 pounds in seawater. Test load L2, the block, was 4 feet square, 2 feet high and weighed 4,500 pounds in the air and 2,760 pounds in seawater.

Winches. A hydraulic traction winch was used to handle the lift line during testing. This winch did not have any motion-compensation capability. For the guidelines, two large-capacity, air-operated winches were used to deploy the guideline anchors and to maintain constant tension in each guideline.

Procedures

Throughout the shallow-water tests, the surface ship was spread-moored to three buoys to maintain position.

The anchor block with guidelines attached was first lowered to the seafloor to establish a guideline system. The guideline tension was set at approximately 2,000 pounds. The guide frame and payload were then rigged to the lift line and, for the shallow-water tests, lowered to depths of 50, 150, 300, and 500 feet. At each depth, the payload was stopped and allowed to stabilize for about 3 minutes. For the return trip, the guideline tension was reduced to 800 pounds. The payload was again stopped at each depth for 3 minutes.* The self-recording current meter attached to the guide frame and guide cone recorded current speed and direction and the orientation of the guide frame. After the payload reached the surface, the payload or the guide frame was changed for the next test run. The amount of drift of the surface ship after the guideline was established was determined by a transponder system on the seafloor for the shallow-water tests.

For the deep-water and the anchor-mating test runs, no stabilizing stops were made during the lowering or raising of the payload. Lorac B navigation was used to help the surface ship maintain station. A taut buoy system was established at the test site to provide visual aid to the pilot.

*The procedure was slightly different in tests 7 and 8: the lowering used the same technique, but the system was raised to 150 feet without pausing, the tension was reduced to 800 pounds, then lowered to 500 feet with the normal 3-minute intervals. Finally, it was raised to the surface without stopping.

DISCUSSION OF RESULTS

Entanglement

Only three entanglements were observed during seventeen tests; two of these entanglements occurred during the anchor-mating tests and the other one during a deep-water test.

As the guide frame emerged from the water near the end of deep-water test D1, it was observed that the guide frame had rotated 360 degrees from its initial orientation. The rotation recording (Figure 9) indicated that the entanglement was formed near the seafloor and had been pulled all the way to the surface. However, the entanglement did not cause any damage to the guideline system and did not delay the hoisting operation. Technically, the system was entangled; but, practically, the entanglement was not serious.

Both anchor-mating test runs, one in 600-foot depth and one in 4,500-foot depth (Tests M1 and MD-1) ended with serious entanglements. When the add-on block was retrieved with the anchor block, the lift line and the guideline were twisted about five times. Since in both cases the add-on block reached the anchor block on the seafloor, the entanglement must have occurred during retrieval of the assembly with both lift line and guidelines.

Guide-Frame Motion

The rotation of the guide frame is considered an index of the stability of the guide-frame/payload system. If the rotational displacement of the guide frame is large, the system is considered unstable and is liable to become entangled with the guideline. The rotation was measured by a compass inside the Geodyne current meter mounted on the guide frame.

During processing of the recording film, the data from the double guideline tests in shallow water (Tests 1 through 4) were lost; the remaining shallow-water data are presented in Table 2. Of the varied parameters of Table 2, only three have a strong effect on guide frame rotation--the guide frame span (the distance between lift line and guideline supports); the submerged weight of the test load; and the guideline span (the horizontal distance between anchor point and the surface support point). The effects of the guide frame span and the submerged weight of the test load are shown in Figure 10. The initial orientation of the guide frame at the surface was 330 degrees from North in the clockwise direction. The prevailing current direction is about 280 degrees from North (coming from East). Almost all rotations of the guide frame with heavy test loads were clockwise, with respect to the initial guide frame orientation, whereas the guide frame with a light load rotated only in the counterclockwise direction. The rotational displacement is found to be inversely proportional to the guide frame span, suggesting there is a constant, relative, current-induced, linear displacement between the lift line and the guideline.

Table 2. Rotation Data for Single Guideline Test at 600-Foot Depth

Test No.	Submerged Weight of Load (lb)	Guide Frame Span (ft)	Guide-line Tension (lb)	Guide-line Span (ft)	Guideline Direction (deg)	Depth (ft)	Current Speed (ft/sec)	Current Direction (deg)	Guide Frame Orientation (deg)	Twist Oscillation (deg)
5	5,560	9	2,000	3	150	150	0.85	320	-40	0
			2,000			300	0.63	345	-15	4
			2,000			500	0.43	345	10	2
			800			500	0.38	345	15	2
			800			300	0.60	330	15	3
			800			150	0.71	330	-10	5
6	2,760	9	2,000	7	140	10	0.62	300	-25	3
			2,000			150	0.71	300	-80	5
			2,000			300	0.43	345	-110	7
			2,000			500	0.29	345	-120	13
			800			500	0.40	345	-130	10
			800			300	0.55	255	-85	7
			800			150	0.76	230	-80	15
7	2,760	6	2,000	7	230	10	0.95	310	-25	20
			2,000			150	0.95	345	-110	20
			2,000			300	0.40	320	-115	10
			2,000			500	0.35	345	-140	30
			800			150	0.90	345	-150	10
			800			300	0.45	340	-125	7
			800			500	0.30	330	-130	5
8	5,560	6	2,000	9	280	10	0.80	300	-25	5
			2,000			300	0.67	340	20	13
			2,000			500	0.37	345	30	5
			2,000			150	1.00	340	20	5
			800			150	0.97	345	40	7
			800			300	0.70	345	45	6
			800			500	0.32	345	35	5
9	5,560	3	2,000	5	80	150	0.52	300	50	40
			2,000			300	0.42	345	70	10
			2,000			500	0.34	300	70	20
			800			500	0.36	300	60	15
			800			300	0.52	340	50	10
			800			150	0.55	300	40	20
10	2,760	3	2,000	8	180	150	0.60	290	-150	15
			2,000			300	0.41	300	-130	15
			2,000			500	0.30	300	-180	10
			800			500	0.30	300	-120	10
			800			300	0.52	345	140	20
			800			150	0.62	300	90	25
12	2,760	3	2,000	52	320	150	0.40	300	-170	7
			2,000			300	0.45	315	-140	12
			2,000			500	0.29	305	-150	18
			800			500	0.27	305	-130	12
			800			300	0.74	345	-180	20
			800			150	0.50	300	80	20

Note: All angles were measured from initial guide frame orientation at surface.

The effect of the guideline anchor on the guide frame rotation along the guideline length can be visualized as shown in Figure 11. The orientation of the guide frame depends on the relative position of the lift line and the guideline. The position of the payload is mainly controlled by the prevailing current speed and direction. The position of the payload as projected on a horizontal plane, together with the guideline, are shown in the plan view. Note that the guide frame rotates a substantial amount from the surface to the seafloor. The effect of the guideline tension, the suspension depth, and current conditions could not be identified due to the scatter of the data. The measured data indicate little dynamic activity of the guide frame. About 90% of the rotational oscillations have a peak-to-peak value of 20 degrees. The maximum recorded variation is 40 degrees. The payload/guide-frame system is, therefore, considered stable.

It is not likely that surface excitations could trigger a large amplitude oscillation that would eventually lead to entanglement. The main conclusion of the shallow-water, single guideline tests is that the rotational motion of the guide frame depends solely on the static forces acting on the whole cable system rather than the dynamic excitations applied from the top. In other words, the decoupling of the surface effect from the guideline system is quite effective.

For a general guideline design it is not required to know the orientation of the guide frame at various depths: the only concern is the entanglement. If a complete solution of the guideline system is required, the problem can become quite difficult. Methods are available for the solution of complex three-dimensional cable structures, but the task is by no means small (Reference 7). Appendix A presents an approximate solution for a quick analysis of the guide frame rotations. This method is presented here for those who wish to make a qualitative analysis of the payload orientation at various depths along a single guideline. Based on the relative guideline displacement concept, the direction of guide frame rotation can often be predicted without any calculation.

The results of the deep-depth tests are presented in Figure 9. All three test runs are stable, but the rotations are usually sudden. Apparently, the rotations are results of readjustment of the equilibrium position. Dynamic oscillation is not observed. The double guideline tests seem to have more stable motion throughout the tests--near the surface, in particular. If bottom mating and orientation control are not required, a single guideline is considered effective for entanglement-free operations.

The entanglement observed in test run D1 was probably caused by an unexpected slack developed at the lower end of the guideline. The upper end of the guideline was tensioned by an air-operated winch, which, however, must have failed to develop enough tension to support the entire weight of the guideline. This winch could not maintain constant tension when working at the lower end of its rated load range. A smaller winch would provide better tensioning, but the spool would be too small for

the long guideline; and its maximum capacity would be too small to deploy and recover the guideline anchor. Had the guideline been lightweight ropes, slack at the lower end might have been avoided. For best results in future designs, the guideline should be high-strength, lightweight ropes, such as the newly developed ropes made of Kevlar 29 and Kevlar 49 materials, to take reasonably high tensions with less tension variations along the line.

Deck Handling

The guide frame and the payload can be attached to the guideline system either on deck or under the surface by divers. The method used in this study was to attach the guide frame on the deck of the support vessel. The payload assembly was first placed under the bow A-frame by a deck crane. The load was then transferred to the lift line support by a block.

Sometimes the payload swung, and it was quite difficult for the riggers to align the guideline with the slots on both upper and lower guide cones. The problem was solved by reducing the number of guide cones to one on the single guide frame and to two on the double guide frame, thus enabling the riggers to quickly place the guideline into the guide cones.

Another problem that was encountered with the single guide frame was its tendency to tilt from its own dead weight when suspended by the lift line. A tilted guide frame will not slide properly on the guideline and also makes it impossible to place the guideline into the guide cone. A straightforward solution to the problem was to attach a short length of chain across the top of the guide frame and to shackle the lift line to a selected point on the chain to level the guide frame (Figure 12). Because these problems were not severe, it is felt that deck rigging by riggers is superior to underwater rigging by divers.

The method of using two parallel guidelines for lifting and lowering the anchor block proved completely successful. The positive control of line tensions by air-operated winches and the low center of gravity of the payload contributed greatly to the entanglement-free operation.

Motion Compensation

Large dynamic tension was observed by a load cell when the load was suspended at the 50-foot depth. However, the resiliency of the nylon lift line was effective in providing motion compensation at depths beyond 300 feet. At the 600-foot depth, the dynamic tension in the nylon guideline was so small that the air winches did not operate. Therefore, surface motion compensation was not needed for the long nylon guidelines.

For guidelines of steel wire ropes, the air winch worked as expected. The dynamic tension in the guideline was greatly reduced by the motion compensation. The guideline tension was always kept near a preset value.

However, for the 4,500-foot depth the amount of elongation of the steel wire rope was large enough to maintain a taut guideline even though the surface fluctuation was about 4 feet. Therefore, motion compensation is not as critical for nylon ropes as it is for wire ropes nor for deep depths as it is for shallow depths. The high dynamic tension that can occur during the deployment of the guideline anchor block could dictate the use of the motion-compensating winch as the lifting equipment. After deployment the upper end of the guideline can be hard-stopped at the deck.

Guideline Hardware

All of the guideline hardware functioned as designed except for the mechanical release. A spring fell off in each of the anchor-mating sea tests. This was one of the main causes for the line entanglement during the mating tests. Stronger springs and better terminations are the logical improvements. A method for preventing the rotation of the payload during vertical movements should be sought.

Anchor-Mating Experiment

Although the mating operation was successful during the dry land trials, both sea tests (Figure 13) were unsuccessful. In addition to the malfunctioning of the mechanical release, the rotational behavior of the payload in the water column under the hydrodynamic drag may have contributed to entanglement, leading to the failures. Any asymmetry of the payload about a vertical axis can cause the payload to rotate about its vertical axis in vertical motion. Since the lift point of the payload is practically touching the guideline, the lift line tension would not yield any righting moment to counteract the rotation induced by the flow drag. It is still considered feasible to complete a remote seafloor mating using an improved mechanical release and a much slower lowering speed. The effectiveness of the bottom guidance device, such as the guide post, was inconclusive due to the failure of the mating exercises. Underwater observance, such as with an underwater television, is highly recommended for future mating tests.

FINDINGS

1. Only one line entanglement was observed during thirteen sea tests, excluding the anchor-mating tests. That entanglement was probably caused by undetectable slack at the lower end of the guideline. Most of the static rotations of the guide frame were smaller than 180 degrees. Both double and single guideline systems are considered safe to operate to depths of 4,500 feet. Entanglement-free operation was made possible by the use of nonrotational ropes and air-operated winches for surface motion compensation.

2. The motions of the payload in the water column were stable, and the position of the guide frame was dependent solely on static forces. The dynamic motions of the payload were negligible under the prevailing current of 0.4 to 1.0 knot.

3. The basic design of the hardware for the single and double guideline systems was generally adequate.

4. The mating of two anchor blocks on the seafloor was not successful during the sea tests. The handling hardware needs improvement.

5. The basic recommendation for guideline system design and operation: do not allow the accumulation of torque or the relaxation of tension in the cable system at any time.

CONCLUSIONS AND RECOMMENDATIONS

Design of the Guideline System

Guideline. The tension, type, size, and rotational qualities of the rope are extremely important in designing or selecting the guideline to be used in the system to ensure entanglement-free operation.

1. Tension. Guideline tension should be as high as possible to maintain positive control of the payload motion. In most cases, the recommended guideline tension would be the lift line tension divided by twice the number of guidelines. Double guidelines would require only one-half of the tension required by the single guideline. The lower limit of the guideline tension could be as low as 10% of the lift line tension and still provide satisfactory restriction to payload motions with minimum surface wave and current excitations.

2. Type. Synthetic ropes are recommended for all short-term, low-tension guidelines; steel wire ropes are recommended for long-term, shallow-water guidelines; and Kevlar 29 rope, even though it was not field-tested, is recommended for deep-depth guidelines. Each type of rope has characteristics that have influenced these recommendations. Synthetic rope, jacketed steel wire rope, and three-strand wire rope exhibit poor abrasion resistance (the abrasion resistance of Kevlar 29 rope is still unknown). Improvement of the guide cone design could lower the abrasion-resistance requirements of the guideline. Steel wire ropes are too heavy for deep depths; synthetic rope and Kevlar 29 rope are both lightweight, but the latter's high-strength characteristics recommend it, in addition. Six-strand wire ropes have better abrasion resistance than three-strand ropes, but the rotational properties of the six-strand ropes are not as good as the 3 x 19, torque-balanced ropes.

3. Size. The size of the guideline depends on the required guideline tension and the weight of the anchor, which, in turn, depends on the tension requirement. If lightweight anchors are to be used, such

as an explosive anchor, the design tension is often governed by the operation tension. But if clump anchors of the gravitational type are to be used for the guideline, the design tension is often the maximum deployment tension. The dynamic tension caused by surface excitations can be calculated by a method presented in both References 8 and 9. Surface motion compensation methods should reduce considerably the dynamic tensions. Size of the lift line for the payload package should be chosen in a manner similar to that of choosing the guideline.

After both the guideline and the lift line are selected, the possible payload rotations should be checked, using a design current profile and various guideline tensions. One should chose a larger-sized guideline if required.

4. Rotational Qualities. Nonrotational or low-rotational rope construction is essential in preventing kink formations in the guidelines. A roller-bearing swivel should be inserted between the guideline and the guide post or anchor block (see Figure 3).

Appendix B presents a method for calculating the rotation of a payload along a single guideline caused by the torque in the lift line, neglecting the wave action and the current drag. This method is useful in designing high-tension guideline systems for heavy payloads in shallow depths.

Anchor.

1. Weight. To prevent possible movement of the anchor on the seafloor, the weight of the anchor should be at least 50% higher than that required for the guideline operational tension. Either steel or concrete can be used for making gravity anchors. The steel anchor, with its small volume, is easier to handle on the surface. Concrete, less expensive, can be cast into any shape.

2. Guide Post. The guide post on the anchor block is used only for bottom guidance when seafloor mating of a payload to an anchor block is expected. Two guide posts on an anchor block can provide fine guidance for the alighnment of payloads. The maximum stress on the guide post would occur when the anchor block is being lowered to the seafloor at a tilted position. A large moment could be created at the base of the post, and this must be considered in the design.

The length of the guide post is determined by the position of the guide cone on the guide frame. The guide post should be long enough to mate completely within the guide cone. For best mating results, the guide post should be as free of protrusions as possible (see Figure 3).

Guide Frame. The configuration of the guide frame depends largely on the geometry of the payload package. The horizontal dimension of the frame (i.e., the spacing between the lift line and the guideline) should be as large as possible, but the size of the guide frame should not be so large that smooth handling of the payload package is jeopardized. The frame should be tall enough that the guide frame can always be maintained in a horizontal position by applying vertical tensions on the side members.

If the payload is not to be separated from the guide frame and the payload is bulky, it is advisable to weld the guide cone directly onto the side of the payload.

To avoid hydrodynamic instability during descent or ascent, the whole payload package and the guide frame should be as symmetrical as possible. Vertical vanes can be added to the payload package to stabilize possible rotational motion.

For each guideline there should be one guide cone with both upper and lower skirts afixed to the guide frame. The guide cone should be designed to quickly open and close for the enclosing and releasing of the guideline. A quickly operated latch is needed for this purpose. The tube section of the guide cone should be reinforced with collars, and the latch should be capable of transferring the circumferential load in the tubes. The internal surface of the tube should be clear and smooth to avoid abrasion of the guideline. The diameter of the tube depends on the size of the guideline or the diameter of the guide post. The inner diameter of the tube should be larger than the outer diameter of the guide post for a smooth fit. Sliding of the tube over ordinary wire rope can create abrasion grooves on the tube wall. A set of roller bearings installed in the guide cone can effectively prevent abrasive wear to the tube and to the guideline. Low friction plastic should be considered as an alternative to roller bearings to reduce abrasive wear on synthetic lines. The tube should be short enough to reduce the friction, but long enough to obtain righting moment against tilting of the guide frame during deployment.

Operation of the Guideline System

Two basic rules must be followed in order to ensure a guideline system free of entanglements:

1. Reduce or compensate the surface motion of the platform so that at no time shall the tension in either the guideline or the lift line be zero.

2. Provide every possible means to release the in-line torque in both the lift line and the guideline.

Those factors that enable the fulfillment of these basic rules are discussed in the following sections.

Surface Platform. The first step of the guideline operation is to position the surface ship over the proposed anchor site. The position of the ship is monitored by a navigational system, such as Lorac. In shallow water the ship can be moored to maintain station. However, in deep water, the ship must be capable of maintaining station by means of a dynamic positioning system. The maximum drift of the ship should not be more than 10% of the working depth. For more precise measurement of the anchor landing position, an underwater acoustic transducer system can be used. For instance, a three-transponder system was used in the SEACON I project [6].

Anchor. After the surface platform is in position, the guideline is established. The anchor can be lowered by free fall or by lowering from one or more guidelines. The shape of the anchor directly affects the hydrodynamic stability during a free-fall deployment. Motion compensation or surface action decoupling are definitely required for successful lowering with lines.

Guidelines and Lift Lines. The guideline usually is attached to the anchor during the deployment, but it can be attached to the anchor after the deployment by using manned or unmanned submersibles.

The guideline can also be established by a recall buoy attached to the anchor. Upon a recall acoustic signal the buoy floats to the surface with a messenger line. This line is then used to establish the guideline. Quick-release connectors and submerged winches are needed for such operations.

It is also possible to establish a second guideline using an existing guideline. A release connector is needed for such an operation. Since precise alignment is needed for such matings, a more sophisticated bottom guidance system should be designed and tested before any attempt is made on the remote establishment of a second guideline.

Guide Frame and Payload. The main lift line and the guidelines are supported from a surface platform. The guide frame and the payload can be attached and released from the guidelines on deck or in the water. An A-frame is required, together with other deck load-handling equipment, if the payload is to be rigged to the guideline system on deck (Figure 14). For in-water handling, divers are required. Since the divers have limited communication with the surface and other disadvantages, on-deck rigging of the payload to the guideline system is recommended whenever possible.

Winches. Compensation for motion and decoupling of surface excitations can be provided by constant-tension winches, air-operated winches (Figure 15), and counterweight systems. The method selected depends on anticipated sea state conditions. Since constant-tension winches of large capacities are difficult to locate, pneumatic winches are considered satisfactory. The use of such equipment should be limited to deep water and moderate sea conditions. For mild sea states with smaller surface motions, a counterweight system is satisfactory for reducing surface excitations. The elongation of the nylon rope can provide limited motion compensation, thereby allowing the operation of guidelines without other compensation equipment in deep water.

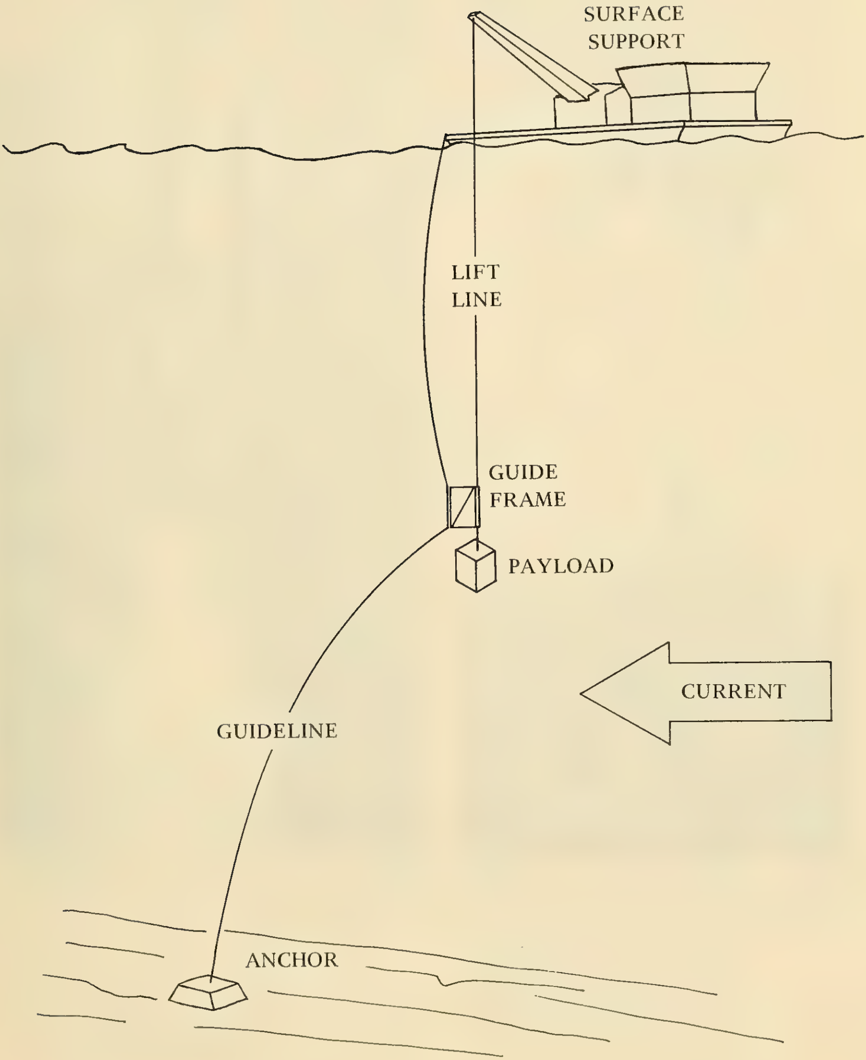

Figure 1. Single guideline system.

Figure 2. Dry land simulation of a double guideline test. Three add-on anchors are seen next to the single anchor block.

Figure 3. Roller bearing swivel relieves torque in guideline. The guideline/guide-post joint is as free of protrusion as possible to avoid line entanglement.

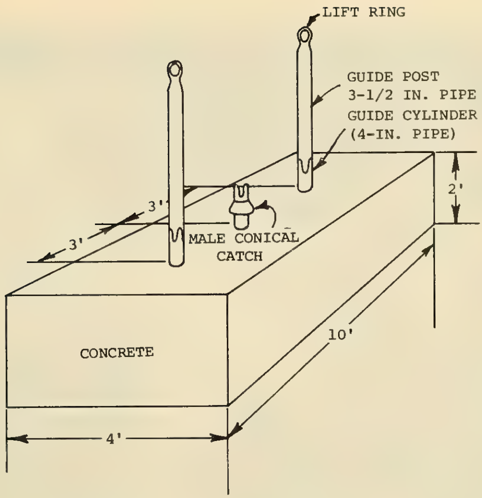

Figure 4. Double guideline anchor block.

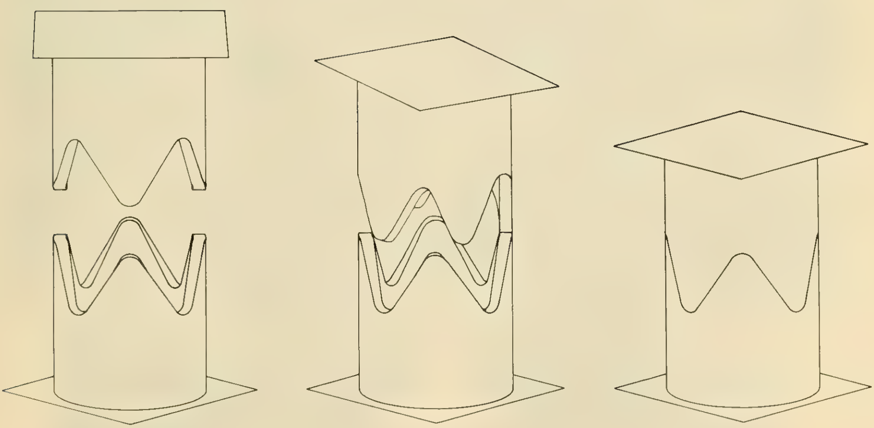

Figure 5. Method of alignment of add-on block to anchor block. The four wedges force the alignment of each cylinder as they come in contact.

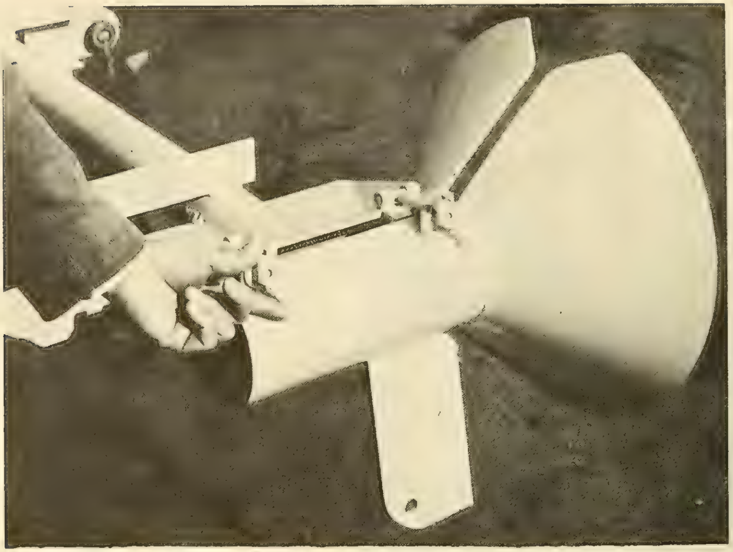

Figure 6. Close-up view of a guide cone

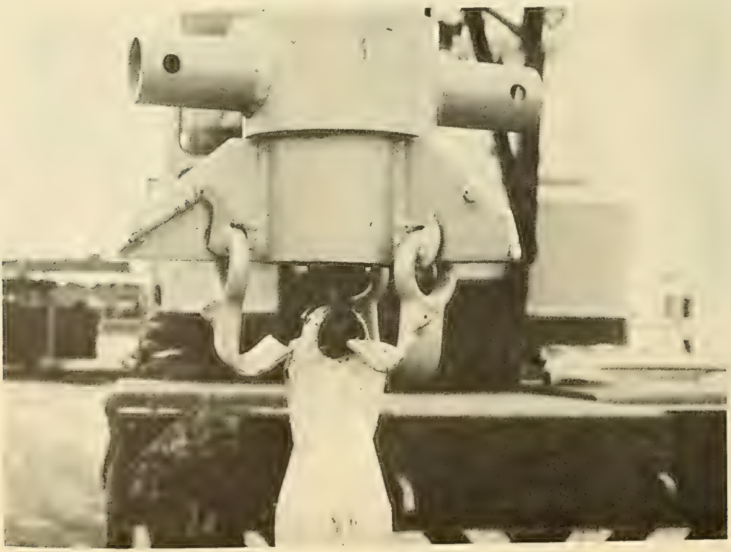

Figure 7. Mechanical release hooks in retrieving position. Upon contact, the male conical catch forces open the hooks until the skirt engages with all the hooks.

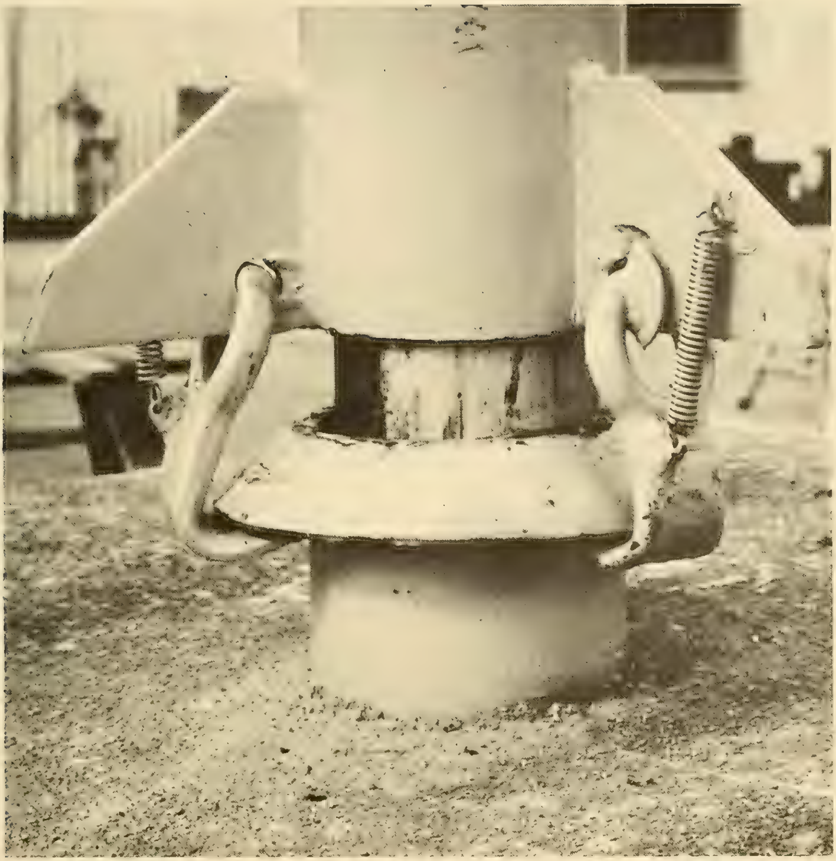

Figure 8. Mechanical release hooks in release mode. When load is removed from hooks, the springs pull the hooks back.

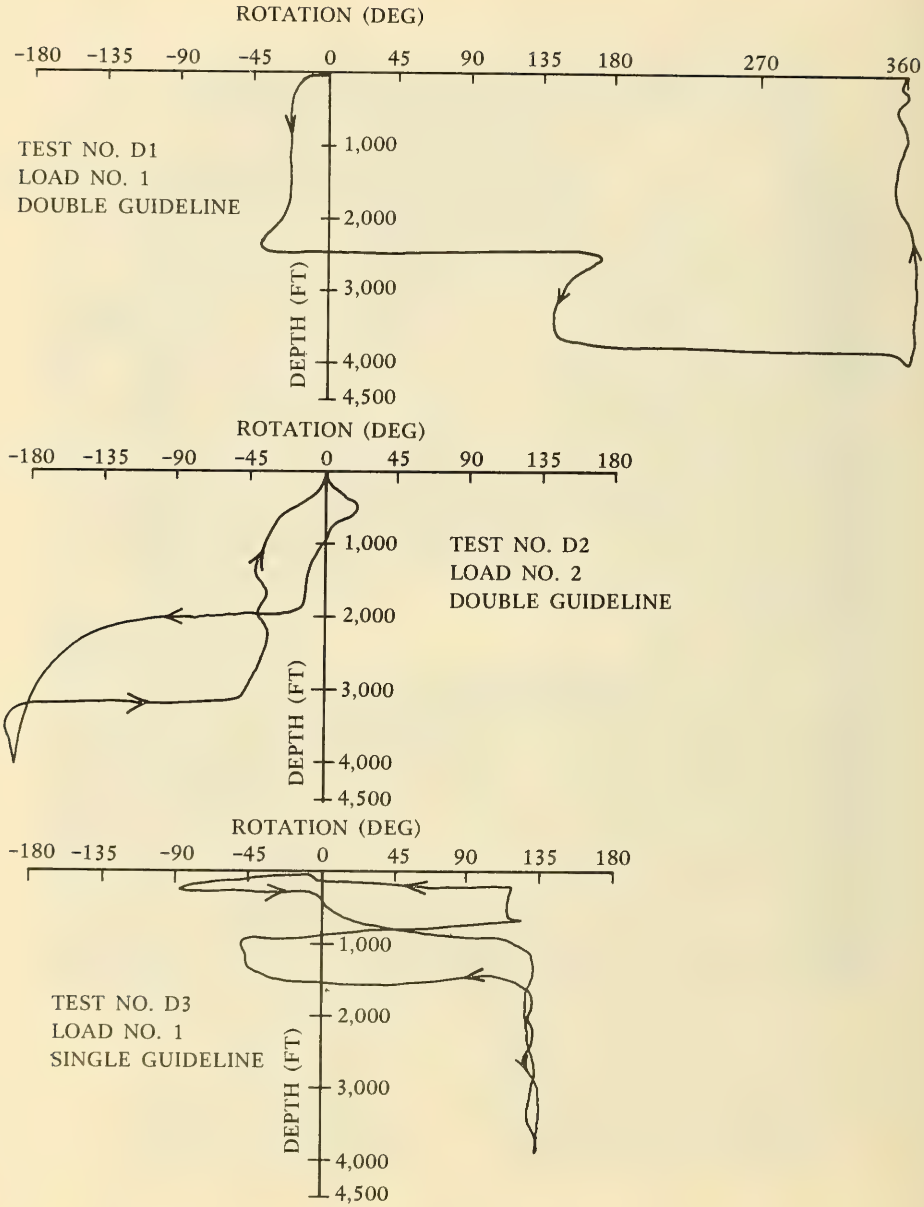

Figure 9. Rotational data for deep-water tests D1, D2, and D3. D1 had an entanglement.

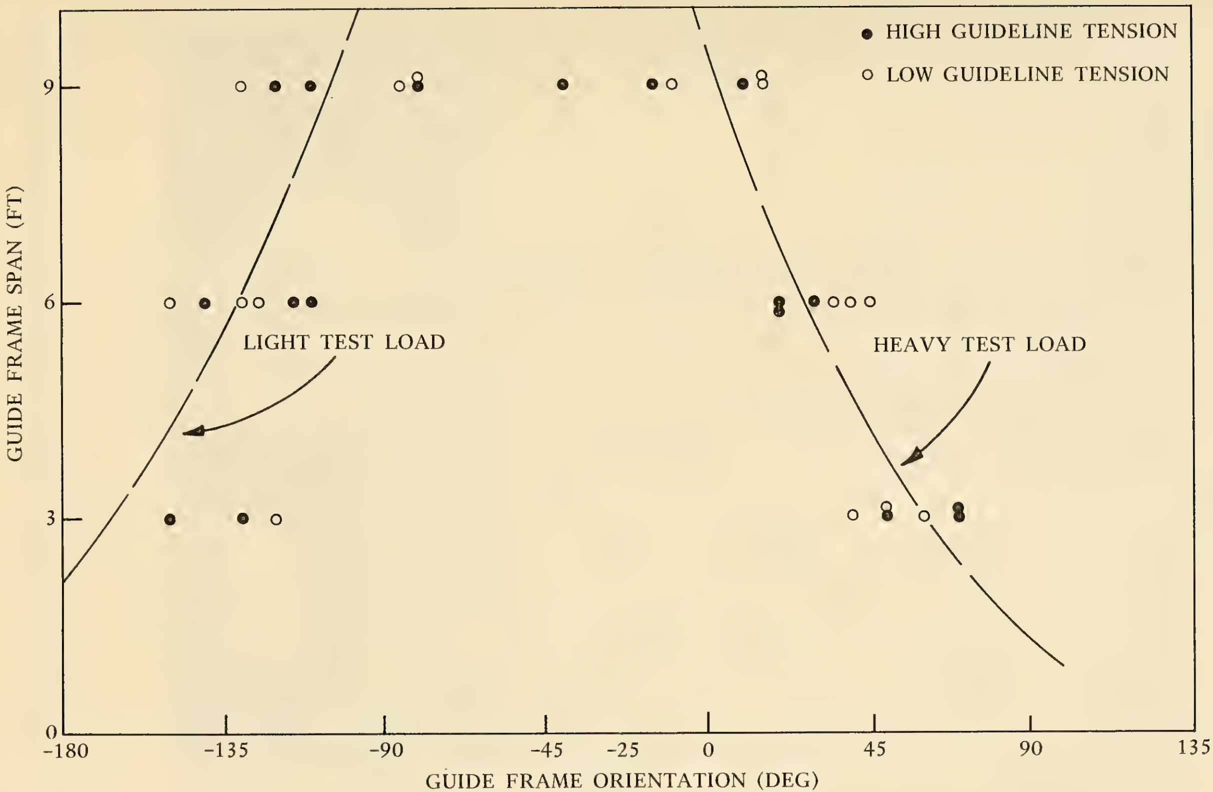

Figure 10. Rotational displacement of single guideline in 600-foot depth.

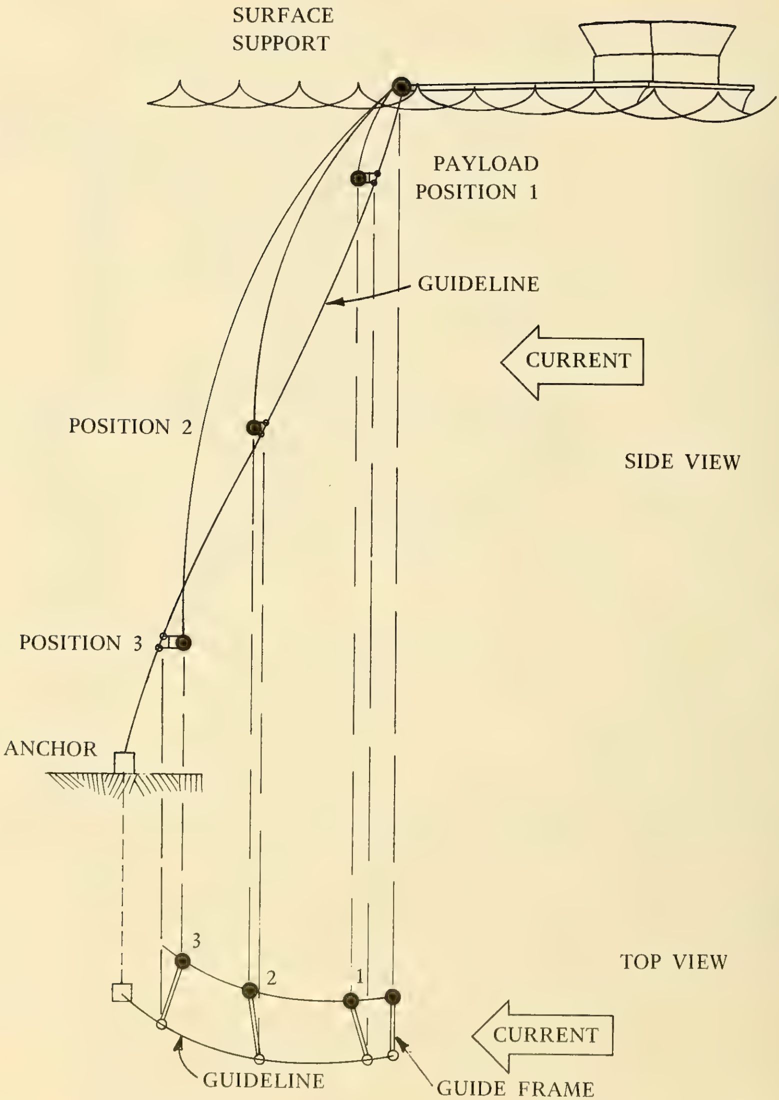

Figure 11. Movement of the guide frame during descent along a guideline with a drift-away anchor.

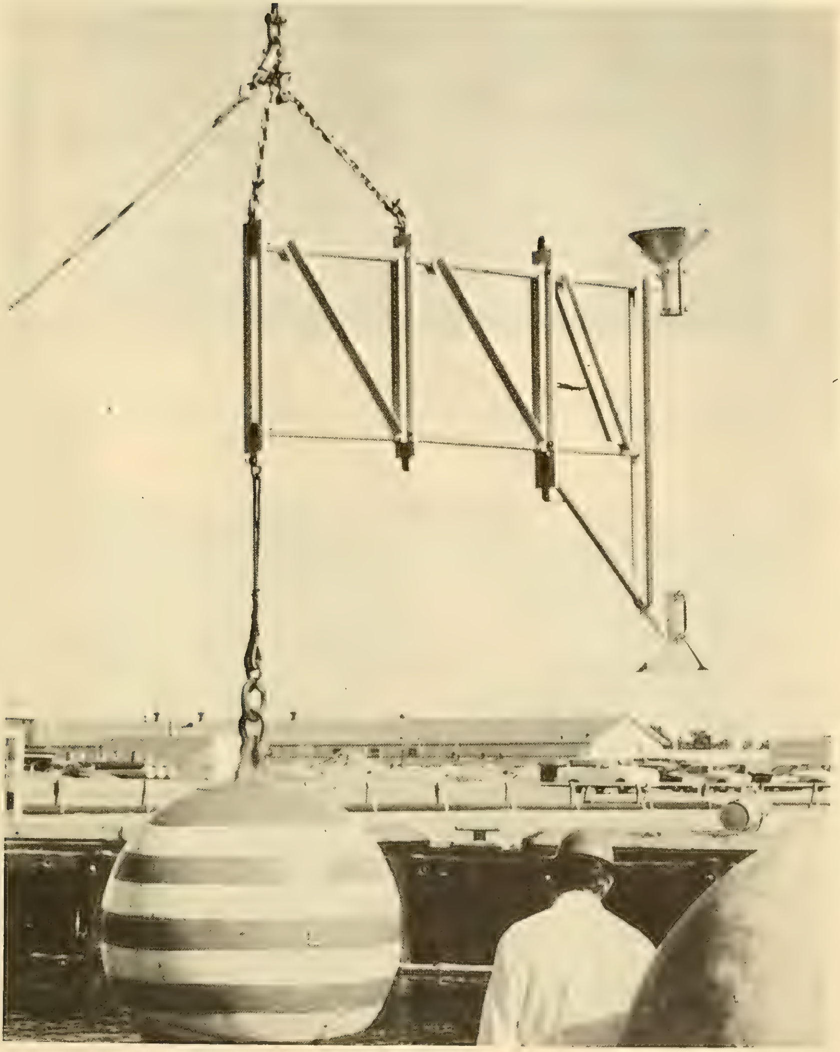

Figure 12. Early version of a single guide frame with a 9-foot span.

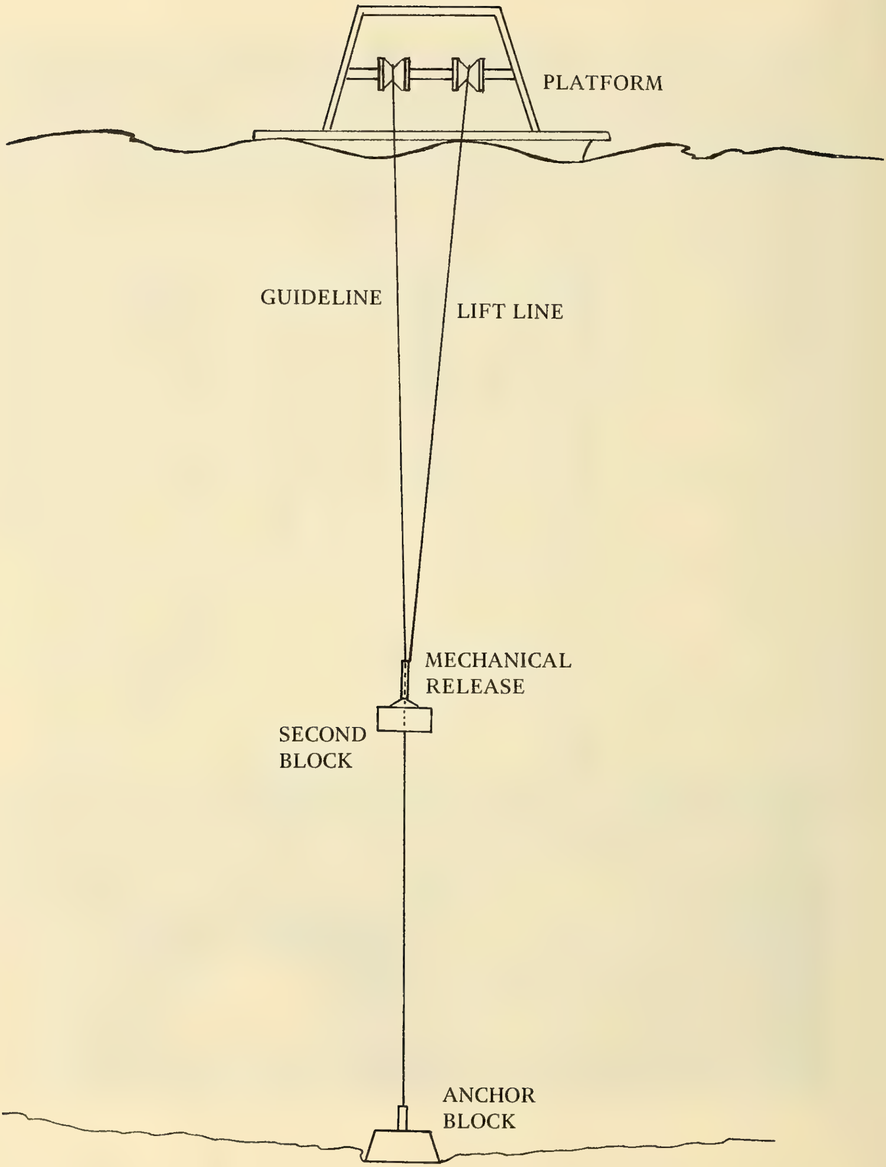

Figure 13. Underwater mating of structural blocks. Without a guide frame, there is almost no restoring moment against payload rotation.

Figure 14. Installation of guidelines in guideline system. An A-frame is used to support the guideline system.

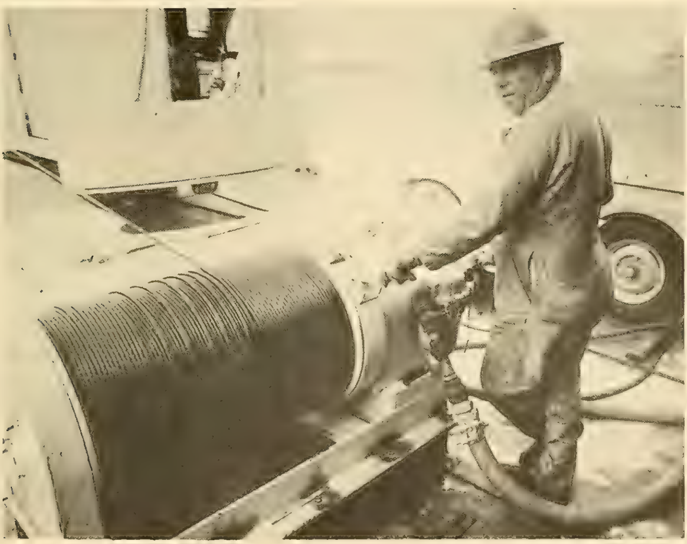

Figure 15. Air-operated winch. Compensates a moderate amount of ship motion to maintain tension in in a guideline.

Appendix A

AN APPROXIMATE STATIC ANALYSIS OF THE SINGLE GUIDELINE SYSTEM

The orientation of the guide frame depends only on the relative position of the payload and the guideline at the depth in question. Figure A-1 is a plan view of a guideline system at the guide frame. The projected positions of the payload and the guideline supports on a horizontal plane are P_o and G_o, respectively. The payload position after horizontal displacement is P. The position of the guideline in zero current is G_1 and, if current is present, G. The guide frame is assumed to be pointing to North at the surface. The current direction is ψ from North. The current speed is assumed to be uniform throughout the depth. The guideline anchor has a horizontal offset of L_{go} in the direction of ϕ from the North. The coordinate system on the horizontal plane has an origin at G_o as shown in Figure A-1.

The final orientation of the guide frame may be approximated by the expression (see Figure A-1)

$$\tan\theta = \frac{X_p - X_g}{Y_p - Y_g}$$

where θ = angular displacement of guide frame from North

$X_p = \ell_{pc} \sin\psi$

$Y_p = S_o + \ell_{pc} \cos\psi$

$X_g = \ell_{go} \sin\phi + \ell_{gc} \sin\psi$

$Y_g = \ell_{go} \cos\phi + \ell_{gc} \cos\psi$

S_o = guide frame length

ℓ = horizontal displacement

The first subscripts p and g indicate the payload at the end of lift line and the guideline, respectively. The second subscripts o and c indicate displacements caused by anchor offset and by current force, respectively.

All external forces acting on the lift line and the payload are shown in Figure A-2 on a vertical plane. Since the current drag is usually small when compared with the total weight of the payload and the lift line, the curvature in the catenary is small. For a first approximation, the lift line is assumed to be a straight line. The total moment about point 0 is zero, and the payload displacement is

$$\ell_p = \frac{D_p Z + D_\ell Z/2}{w Z/2 + W} \qquad \text{(A-1)}$$

where $D_p = C_{dp} A_p \rho V^2/2$, current drag force on payload

$D_\ell = C_{d\ell} d_\ell \rho V^2/2$, unit current drag on lift line

Z = distance from the surface

w = submerged weight of the lift line per foot

W = submerged weight of the payload

C_d = drag coefficient

A = drag cross-sectional area

d_ℓ = lift line diameter

ρ = density of water

V = current velocity

Subscripts p and ℓ distinguish payload from lift line. The displacement of a point on the guideline Z feet below the surface due to the offset of the guideline anchor is:

$$\ell_{go} = L_{go} Z/Z_{max}$$

where subscript g indicates the guideline. Superimposed on this displacement is the displacement ℓ_{gc} due to the current drag. Because the tension in the guideline will be generally high when compared with the total submerged weight of the guideline, the weight of the guideline is neglected. Reference is made to Figure A-3: using parabolic cable approximation, the maximum displacement of the guideline is at mid-depth.

$$L_{gc} = D_g Z_{max}^2/8 T_z \qquad \text{(A-2)}$$

where the unit drag force on guideline is

$$D_g = C_{dg} d_g \rho V^2/2$$

and d_g is the guideline diameter. The current induced guideline displacement at upper half of the line is:

$$\ell_{gc} = 4\ L_{gc}\ Z^2/Z_{max}^2 \qquad \text{for } Z < Z_{max}/2$$

and for the lower half:

$$\ell_{gc} = 4\ L_{gc}\ (Z_{max} - Z)^2/Z_{max}^2 \qquad \text{for } Z > Z_{max}/2$$

By substituting ℓ_p, ℓ_{go}, and ℓ_{gc} (neglecting the weight of lift line w), the coordinates of the payload and the guideline are:

$$X_p = \frac{1}{W}\,(D_p\ Z + D_c\ Z/2)\ \sin\psi \tag{A-3}$$

$$Y_p = S_o + \frac{1}{W}\,(D_p\ Z + D_c\ Z/2)\ \cos\psi \tag{A-4}$$

$$\left.\begin{aligned} X_g &= \frac{L_{go}\ Z\ \sin\phi}{Z_{max}} + \frac{D_g\ Z^2\ \sin\psi}{2\ T} && \text{(A-5)} \\ Y_g &= \frac{L_{go}\ Z\ \cos\phi}{Z_{max}} + \frac{D_g\ Z^2\ \cos\psi}{2\ T} && \text{(A-6)} \end{aligned}\right\}\ \text{when } Z < Z_{max}/2$$

$$\left.\begin{aligned} X_g &= \frac{L_{go}\ Z\ \sin\phi}{Z_{max}} + \frac{D_g\ (Z_{max} - Z)^2\ \sin\psi}{2\ T} && \text{(A-7)} \\ Y_g &= \frac{L_{go}\ Z\ \cos\phi}{Z_{max}} + \frac{D_g\ (Z_{max} - Z)^2\ \cos\psi}{2\ T} && \text{(A-8)} \end{aligned}\right\}\ \text{when } Z > Z_{max}/2$$

Now the angular displacement θ can be obtained by Equation A-1 and the distance between the payload and the guideline is

$$S = \sqrt{(X_p - X_g)^2 + (Y_p - Y_g)^2} \tag{A-9}$$

If $S < S_o$, frame orientation is not stable because of compressive forces acting on the frame.

This method should give the general orientations of the guide frame at various depths during a lowering and recovery operation. More exact prediction can be made by employing more tedious catenary computations for both lift line and guideline under distributed current loads.

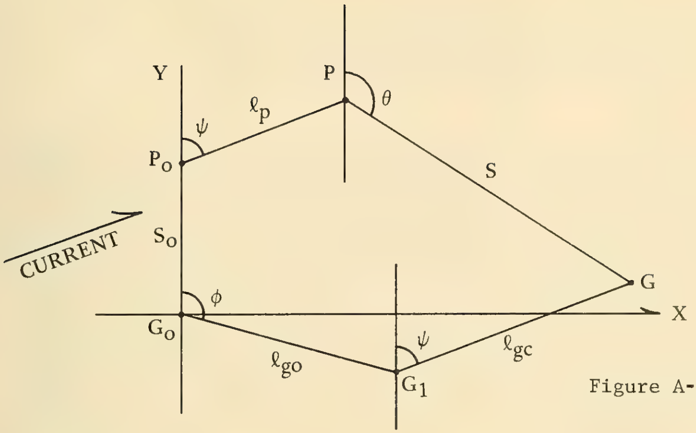

Figure A-1. Displacements of payload and guideline on a horizontal plane.

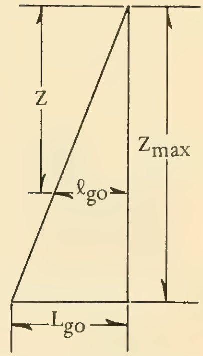

Figure A-4. Guideline offset due to anchor displacement.

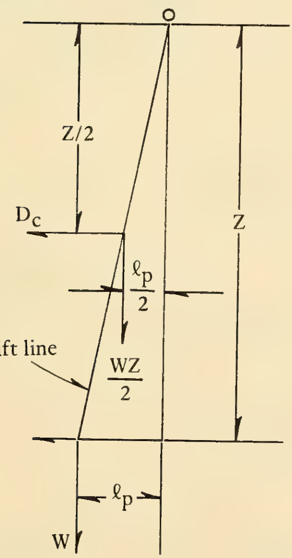

Figure A-2. External forces on a lift line.

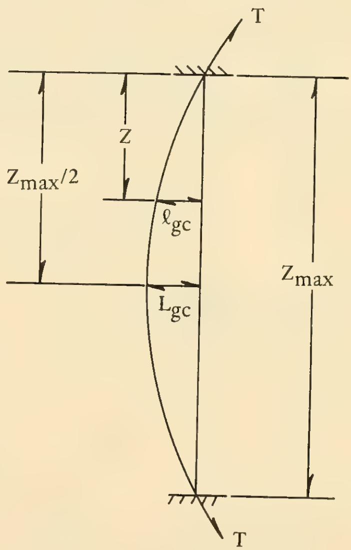

Figure A-3. External forces on a guideline.

Appendix B

RESTRAINING MOMENT BY A SINGLE GUIDELINE

Assuming that wave and current excitations can be completely removed from the guideline system, rotation of the payload must be caused by the torque in the lift line. Such torque is developed in most ropes when under tension. As the guide frame and payload rotate an angle, horizontal components of tensions in both lift line and guideline increase to form a resisting moment until an equilibrium is reached. The amount of rotation as induced by the in-line torque may be solved with the following assumptions: (1) the weight of either lift line or the guideline is to be neglected; (2) the guideline span is zero; that is, the upper end of the guideline support is directly above the guideline anchor point; (3) horizontal current is neglected; and (4) friction at the guide cone is small enough to be disregarded.

This three-dimensional statics problem is solved with basic free-body diagrams. The problem is defined in Figure B-1a (the elevation) and Figure B-1b (the plan view). Line ABC is a single guideline with constant tension T_g, and ED is the lift line with tension, T_ℓ. The payload is suspended at D having a submerged weight of W. The depth of payload is half of the water depth, where the guideline has least restraining power. The guide frame BD has a length of S and is rotated an angle θ due to the lift line torque M.

At equilibrium, a couple F·e is formed to balance the vertical component of external torque M (Figure B-1c).

$$F \cdot e = M \frac{d/2}{\sqrt{b^2 + \left(\frac{d}{2}\right)^2}} \qquad \text{(B-1)}$$

For approximation, $F = M/e$

From free body Figure B-1d, since S << d, therefore a << d/2.

$$F = 2\,T_g \frac{a}{\sqrt{a^2 + \left(\frac{d}{2}\right)^2}} \approx 4 \frac{a\,T_g}{d} \qquad \text{(B-2)}$$

From free body Figure B-1e,

$$F = W \frac{b}{d/2} = 2 \frac{b\,W}{d} \qquad \text{(B-3)}$$

Substitute F into Equations B-2 and B-3 and solve for a and b

$$a = \frac{M\ d}{4\ e\ T_g} \tag{B-4}$$

$$b = \frac{M\ d}{2\ e\ W} \tag{B-5}$$

Since the guide frame length must be S from Figure B-1f, we have

$$S^2 = e^2 + \left(\frac{a + b}{2}\right)^2 \tag{B-6}$$

Substitute Equations B-4 and B-5 into Equation B-6 and solve for e

$$S^2 = e^2 + \frac{\left(\frac{M\ d}{4\ e\ T_g} + \frac{M\ d}{2\ e\ W}\right)^2}{4}$$

$$e^4 - S^2\ e^2 + \left(\frac{M\ d\ W + 2\ M\ d\ T_g}{8\ W\ T_g}\right)^2 = 0$$

$$e^2 = \frac{S^2}{2} \pm \sqrt{\left(\frac{S}{2}\right)^2 - \left(\frac{M\ d\ W + 2\ M\ d\ T_g}{8\ W\ T_g}\right)^2}$$

The angle of rotation is

$$\theta = 2 \tan^{-1} \frac{a + b}{Z\ e}$$

Entanglement occurs when

$$\left(\frac{M\ d}{8\ W\ T_g}\right)^2 (W + 2\ T_g)^2 > \left(\frac{S}{2}\right)^2$$

If Equations B-1 and B-2 are not simplified, more complicated nonlinear equations will be derived; and numerical methods are needed to solve the unknowns a, b, and e.

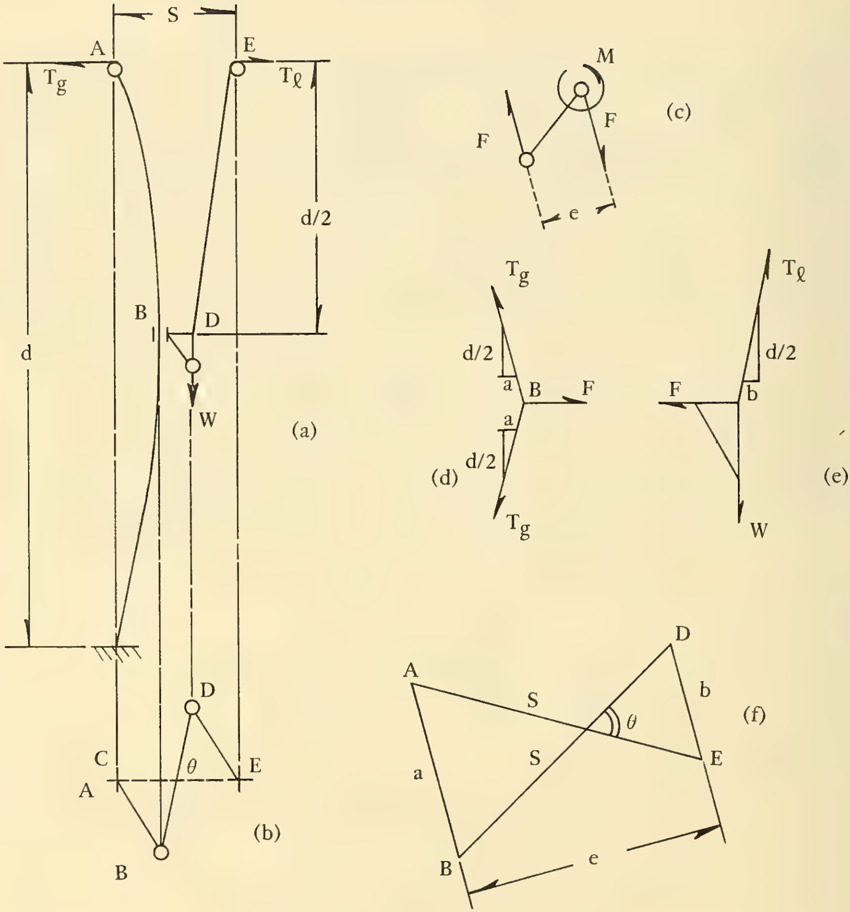

Figure B-1. Solving the three-dimensional statics problem.

REFERENCES

1. Bruce J. Watkins. ''Deep water drilling operations–An integrated subsea drilling system,'' paper presented at the Spring Meeting of the Pacific Coast District, Division of Production, American Petroleum Institute, Los Angeles, CA, May 13-15, 1969.

2. ''Lockheed's subsea celler system,'' Ocean Industry, Vol. 4, No. 8, Aug 1969, pp. 43-45.

3. ''Deep water package may replace fixed platforms,'' Offshore, Vol. 28, No. 9, Aug 1968, pp. 64-73.

4. Edward P. Carpenter. ''Emplacement and recovery of the SEALAB III habitat,'' in Transactions of Symposium of the Marine Technology Society, Oct 20-22 1969, Washington, D.C, pp. 253-266.

5. Civil Engineering Laboratory. Technical Report R- : Seafloor construction experiment; SEACON I–An integrated evaluation of seafloor construction equipment and techniques, by T. Kretschmer, et al. Port Hueneme, CA (to be published).

6. Naval Civil Engineering Laboratory. Technical Note N-1099: Taut guideline for ocean load handling system, experimental results, by H. M. Kusano and C. L. Liu. Port Hueneme, CA, Jun 1970.

7. R. A. Skop and G. J. O'Hara. ''The method of imaginary reactions–A new technique for analyzing structural cable systems,'' Marine Technology Society Journal, Vol. 4, No. 1, Jan 1970, pp. 21-30.

8. Naval Civil Engineering Laboratory. Technical Report R-703: Dynamic stress response of lifting lines for ocean operations, by C. L. Liu. Port Hueneme, CA, Nov 1970.

9.______. Technical Note N-1288: Snap loads in lifting and mooring cable systems induced by surface wave conditions, by F. C. Liu. Port Hueneme, CA, Sep 1973.

DISTRIBUTION LIST

SNDL Code	No. of Activities	Total Copies	
–	1	12	Defense Documentation Center
FKAIC	1	10	Naval Facilities Engineering Command
FKNI	6	6	NAVFAC Engineering Field Divisions
FKN5	9	9	Public Works Centers
FA25	1	1	Public Works Center
–	9	9	RDT&E Liaison Officers at NAVFAC Engineering Field Divisions and Construction Battalion Centers
–	220	220	CEL Special Distribution List No. 11 for persons and activities interested in reports on Ocean Engineering